In-duct air cleaning devices: Ozone emission rates and test methodology

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California Air Resources Board Project #09-342

Final project presentation

Overview: electronic in-duct devices

- California regulates ozone emitting air cleaners
  - Excludes in-duct air cleaners due to lack of test method or lab/field data on ozone emissions
- Central objectives of project
  - Develop test method: ozone emission rate
  - Obtain lab and field data on emission rates and resulting indoor concentrations
- Benefits to California
  - Test method and data to support possible inclusion of in-duct devices in ARB air cleaner regulation

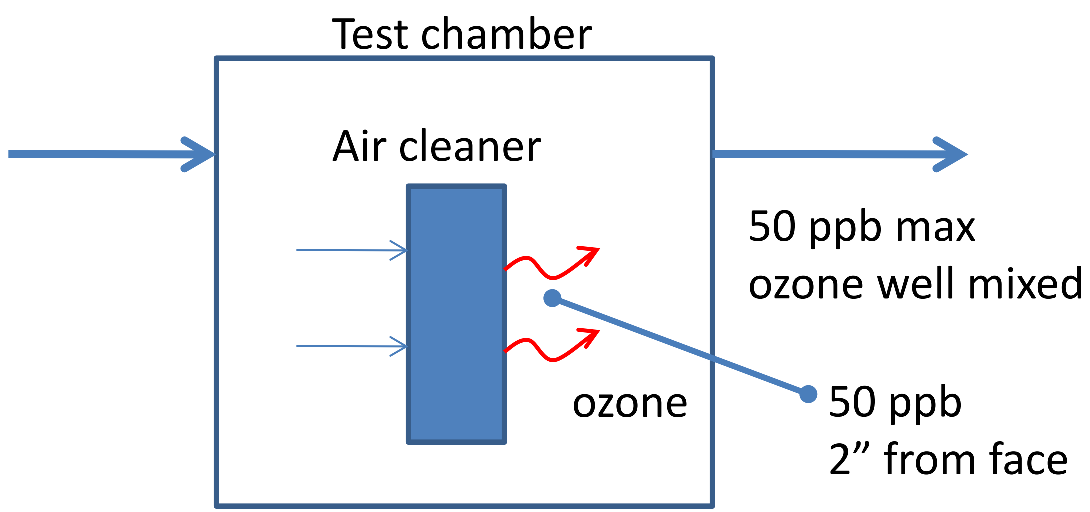
Ozone

- Ozone toxicology highlights
  - 40 ppb NOAEL (Adams, 2002)
- Ozone epidemiology highlights (ambient) (EPA, 2011)
  - Wheezing, difficulty breathing in infants
  - Increased asthma related symptoms and asthma hospital admissions
  - Short term increased mortality

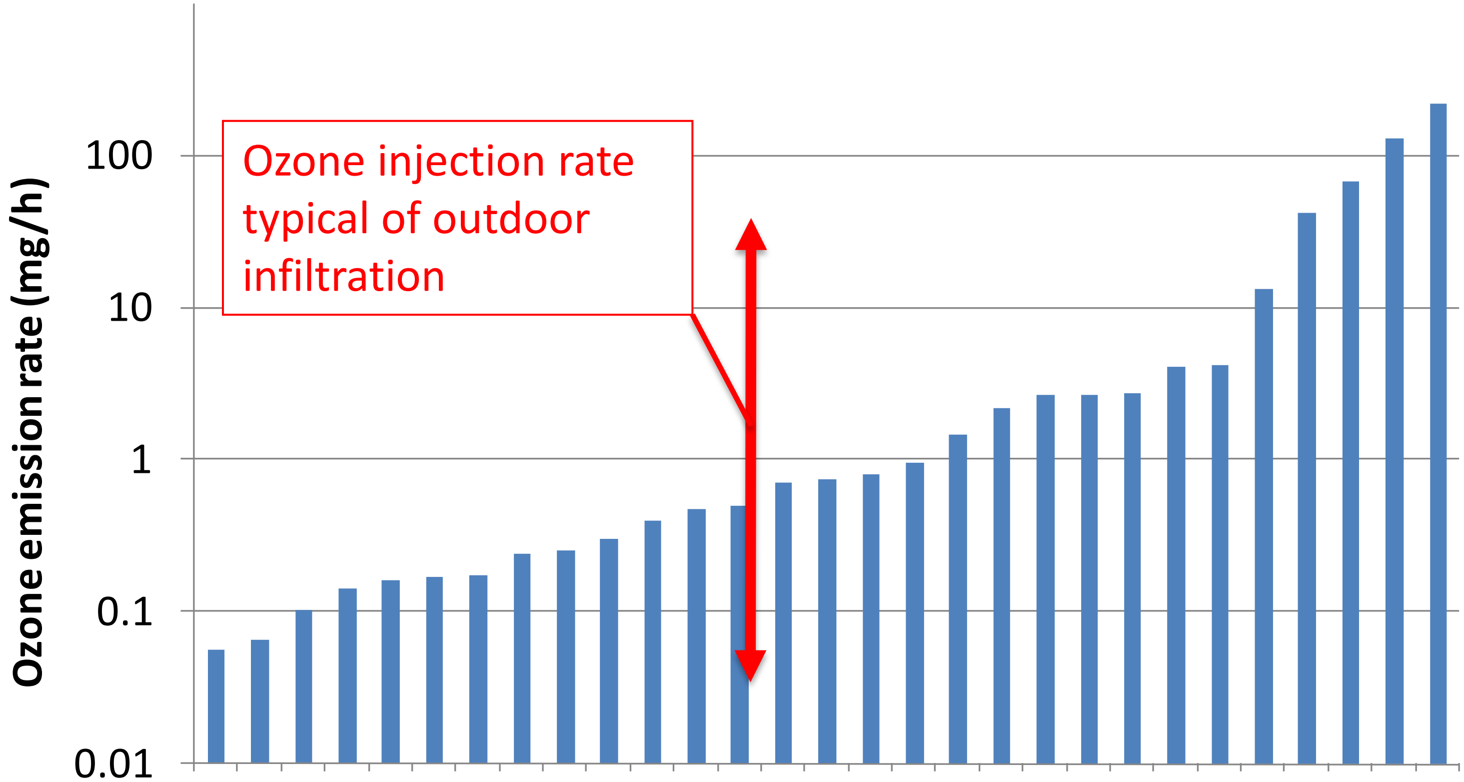
U.S. EPA. Integrated Science Assessment of Ozone and Related Photochemical Oxidants (Second External Review Draft). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-10/076B, 2011.

ARB and UL 867

- ARB air cleaner regulation (2007)
  - Devices tested using UL 867 must meet 50 ppb ozone concentration limit 2” from face



Emission rates of air cleaners



Britigan et al., 2006; Waring et al., 2007; Phillips et al., 1999; Niu et al. 2001a, 2001b; Tung et al., 2005; Yu et al., 2005; Mullen et al., 2005; Siegel et al., 2005.

In-duct, electrically connected air cleaners

- Multiple types
  - Plate and wire electrostatic precipitator
  - Ozone generator
  - Ion generator
- Existing measurements
  - 0-60 mg h^{-1}
    - Viner et al. (1992), Hanley et al. (1995), Bowser et al. (1999)
  - Up to 200 ppb O_3 in house with device installed as directed by manufacturer
    - Emmerich and Nabinger et al. (2000)

Specific Objectives

1) develop and test a method of measuring the ozone emission of in-duct electrically-connected air cleaners (“device”) and
2) obtain real-world data on ozone concentration increases due to use of these devices in field sites
3) apply the method to a number of commercially available units in the lab to measure emission rates, and
4) model the impact of in-duct air cleaners in California buildings.

Tasks

- Task 1. Candidate device survey of in-duct electronic air cleaners
- Task 2. Laboratory development of test method (Objective 1 and 3)
- Task 3. Field testing of in-duct devices and development of field test method (Objective 2)
- Task 4. California field test of 7 homes and 1 commercial building (Objective 2)
- Task 5. Analysis of California homes characteristics and anticipated indoor ozone concentrations (Objective 4)
- Task 6. Project management and reporting

Methods

Task 1

Candidate device survey

- Candidate device survey based on
  - Opinions and experience of California installers
    - 72 contacted, 34 responded
    - “What brands of electronic air cleaners do you sell”
    - “What are your most popular products”
  - California distributors
  - Contacts with manufacturers
  - Opinions and expressed testing interests of agencies (ARB, CPSC, Health Canada, National Research Council of Canada, EPA)

Task 2

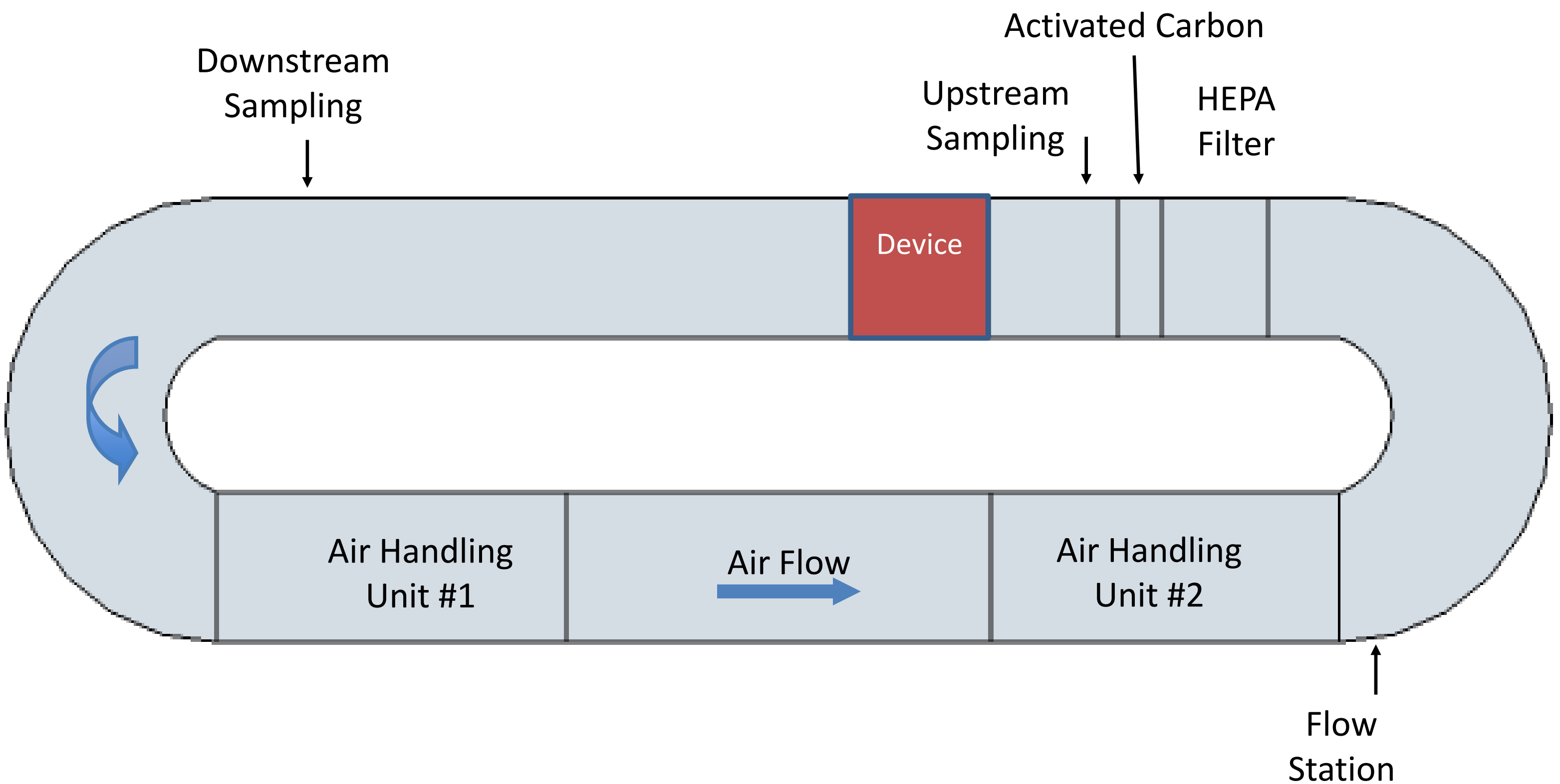
- Develop standard test method
  - Laboratory based
  - Ducted system
  - Realistic operational conditions
  - Range of flow rates
  - Emission rate based on increase in ozone concentration across device:
    - Emission rate = concentration increase* volumetric flow rate

Task 2

- Test apparatus
  - Closed loop
  - Flow up to ~3000 $m^3\ h^{-1}$
  - Able to adjust temperature and RH
  - Activated carbon filtration
  - Able to accommodate wide variety of in-duct air cleaners
  - Ability to measure ozone across installed device

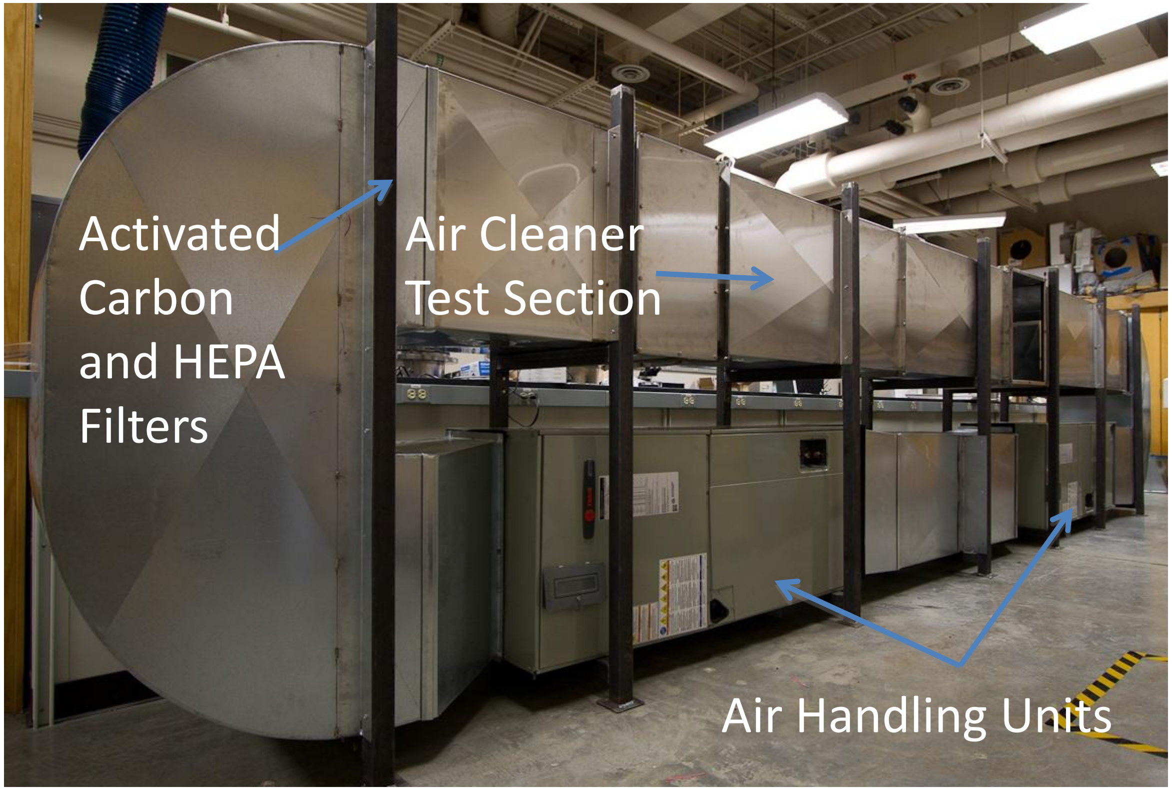
Task 2

- Test apparatus



Task 2

- Test apparatus



Task 2

- Devices
  - based results of Task 1

Air Cleaner	Technology
1	Ultraviolet light
2a	Photohydroionization
2b	Photohydroionization
2c	Photohydroionization
3	Electrostatic Precipitation
4	Photocatalytic Oxidation
5a	Ultraviolet light
5b	Ultraviolet light
6a	Ozone generator
6b	Ozone generator
7	UV / PCO / Carbon
8	Ultraviolet light

Some devices tested





Task 3

- Field tests
  - Method development in Tulsa field site
    - Site selection
    - Incremental increase in ozone concentration
    - In-situ ozone emission rate (OER)
  - Application of method in California field homes
    - Site selection
    - Incremental increase in ozone concentration
    - In-situ ozone emission rate (OER)

Task 3

- Tulsa field site
  - Similar to small California homes
  - Presence of central air system
  - Access to air handler
  - Reviewed 10 houses, chose 1

Task 3

- Field test method (highlights)
  - Measurement objectives
    - Incremental increase in ozone concentration
    - Effective ozone emission rate (OER)
  - Building prep
    - Close windows, doors, fans off (reduce air exchange)
    - Install device
    - Set CO_2 and O_3 sampling locations
      - Supply
      - Return
      - Room center
      - Outdoor

Task 3

- Field test method (highlights)
  - Specific measurements
    - Ozone concentration with device on and off
    - Indoor/outdoor measurements
    - Simultaneous measurement of
      - Ozone decay rate (ODR)
      - Air exchange rate (AER)
  - Effective ozone emission rate (OER)
    - $OER1 = V[(C_{O3})(AER+ODR)-P(AER)\ C_{O3,out}]$
    - $OER2 = (C_{O3}-C_{O3,o})(AER+ODR)V$

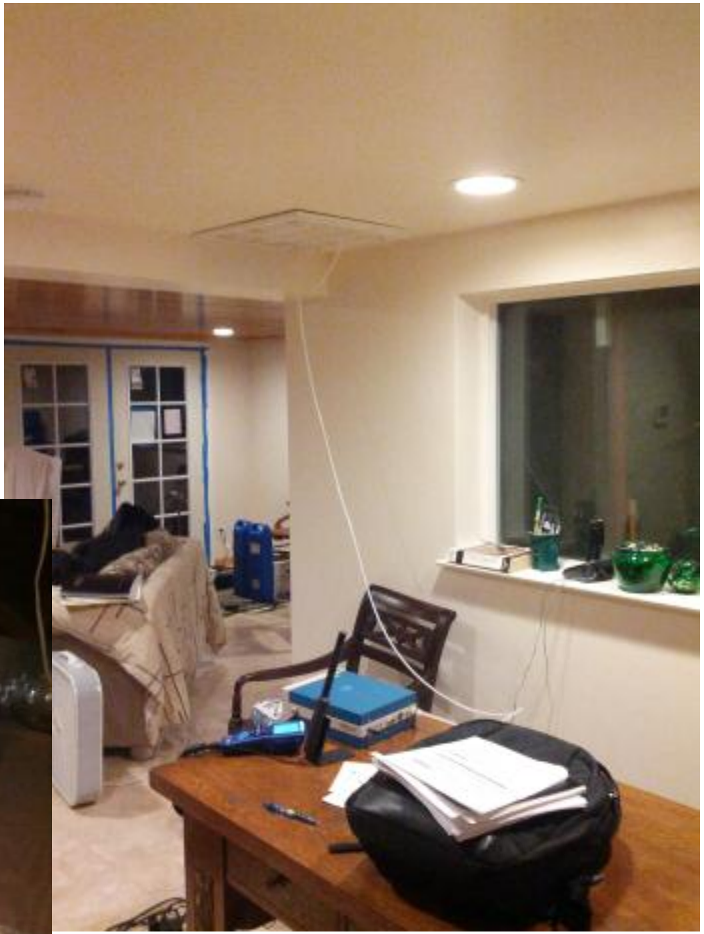
Task 4

- California home selection
  - Installer recommendations
    - Homes with devices already installed
  - Convenience sample
    - List-serves
    - Emails to colleagues
  - Vetting
    - Access, unoccupied during tests
    - Smaller homes (800-1500 ft^2)
    - Appropriate central air facilities

Task 4

- California sites selected
  - 6 homes
    - Single-family residences
    - Davis/ Sacramento area
    - 990 – 2345 ft^2
    - Closet or attic access to air handler
    - 1 to 2 devices tested per home
  - 1 school
    - commercial system pre-installed

Task 4

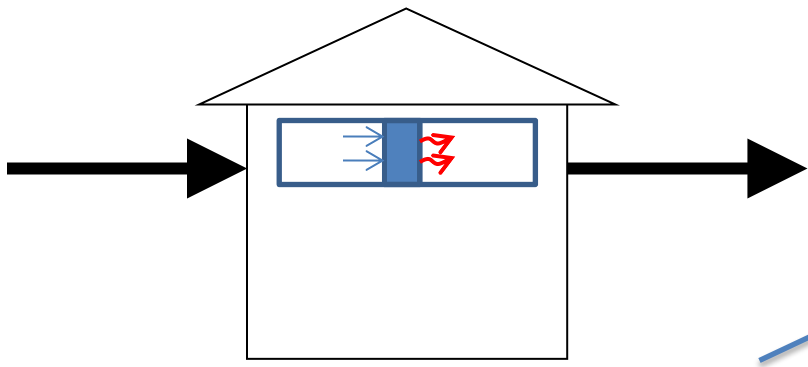


Task 5

- Building simulations
  - Single zone
    - Standard mass balance model
    - California home characteristics
    - Predict range of indoor ozone concentrations
  - Multiple zone
    - Identify complex phenomena
    - Wind induced spatial/temporal “hot spots”

Task 5

Analysis of California homes characteristics and estimated indoor ozone concentrations



Outdoor ozone concentration

Penetration

Effective emission rate

$$C = \frac{V\lambda C_o P_b + S'}{\left(\lambda + \sum_{i=1}^{n} \frac{k_i C_i}{V} + \sum_{j=1}^{m} v_{d,j} \frac{A_j}{V} + (1 - P_r)\lambda_r\right)V}$$

Air exchange rate

Duct/filter/HVAC losses

Ozone decay rate (reactions in gas and with surfaces)

Task 5

- Single zone: model inputs

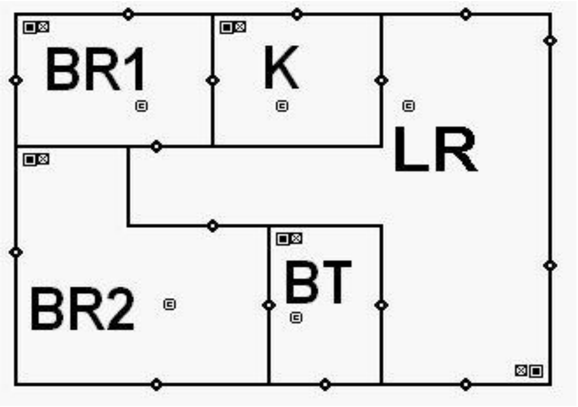
	Low	Middle	High	Standard House	At Risk House
Source emission rate (S'), mg h^{-1}	0	100	300	100	50
Air exchange rate (I), h^{-1}	0.1	0.5	3	0.5	0.1
Volume (V), m^3	75	350	900	350	150
Penetration (P)	0.6	0.8	1.0	0.8	1.0
Decay rate (k_d), h^{-1}	1	4	12	4	1.5
Recirculation air exchange (I_r), h^{-1}	2	5.7	9	5.7	2
HVAC penetration (P_r)	0.75	0.85	0.95	0.85	1
Outdoor concentration (C_o), ppb	0	60	140	0	0

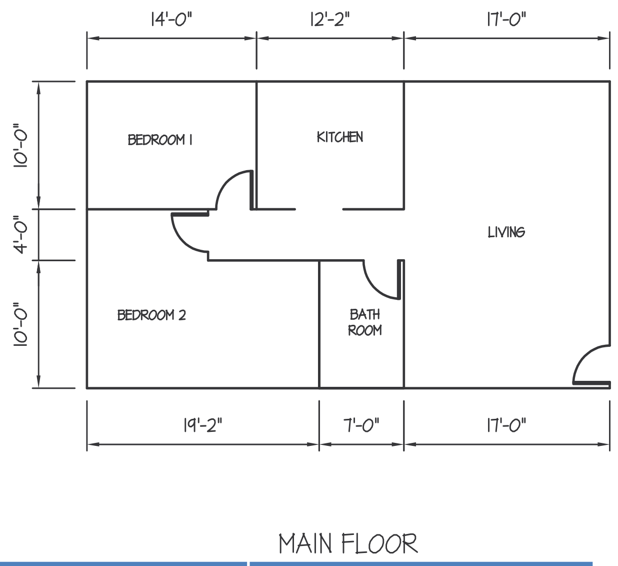
Task 5

- Multiple zone
  - Model framework: CONTAM 3.0 (NIST)
  - Wind speed
  - Wind direction
  - Ambient ozone
  - Variable air handling unit duty cycle
  - Surface reactivity

Task 5

- Building AH-14 (CONTAM)

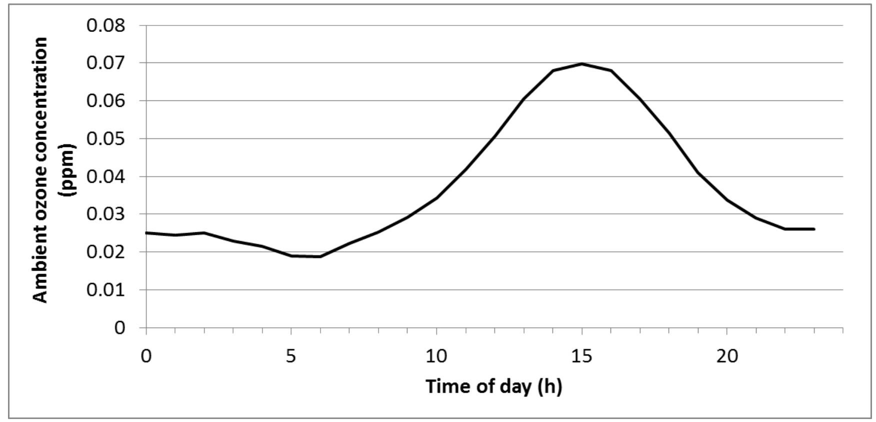




Parameter				
Exterior wall leakage area	0.25	in²/ft²	17.4	cm²/m²
Interior wall leakage area	0.5	in²/ft²	34.7	cm²/m²
Total AHU flowrate	1243	cfm	2113	m³/h
Floor area	1039	ft²	96.5	m²
Volume	8282	ft³	25.0	m³
Interior surface area	4736	ft²	440	m²
Ambient temperature	68	F	20	C
Absolute pressure	14.7	psi	101325	Pa

Task 5

- Ambient ozone



- Simulation parameters

	Wind angle (degrees)					Wind Speed (m/s)			Ambient ozone	Deposition Velocity (m/h)		AHU duty Cycle (%)			
	0	90	135	180	270	2	5	8		0.72	2.0	0	20	50	100
Steady State	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓
Dynamic	✓						✓		✓	✓	✓	✓	✓	✓	✓

Results

Task 1

- Devices that may generate ozone
  - Electrostatic precipitators (EP)
  - Electronically enhanced filters (EEF)
  - Ultraviolet light bulbs (UV)
  - Photocatalytic oxidation (PCO)
  - Dedicated generators of ozone, hydroxyl radicals, hydroperoxide, etc.
  - Hybrid systems (e.g. EP + UV + PCO)

Task 1

- Type of devices tested

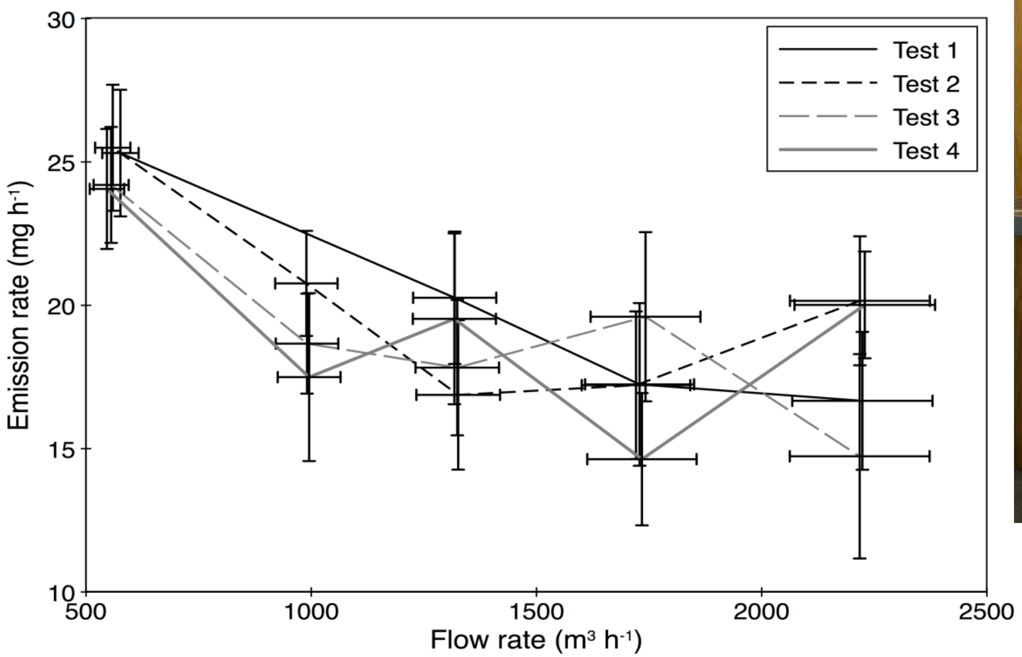
Air Cleaner	Technology
1	Ultraviolet light
2a	Photohydroionization
2b	Photohydroionization
2c	Photohydroionization
3	Electrostatic Precipitation
4	Photocatalytic Oxidation
5a	Ultraviolet light
5b	Ultraviolet light
6a	Ozone generator
6b	Ozone generator
7	UV / PCO / Carbon
8	Ultraviolet light

Task 2

- Standard test method
  - Major sections of device
    - Device test and ozone measurement, Air treatment, Flow generation, Optional conditioning section
  - Measurements and specifications
    - Ozone, Temperature, Flow rates, Relative humidity, Electrical power
  - Detailed reporting and calculations
  - Method qualification and quantification limits
  - Device emission rates over range of flow rates

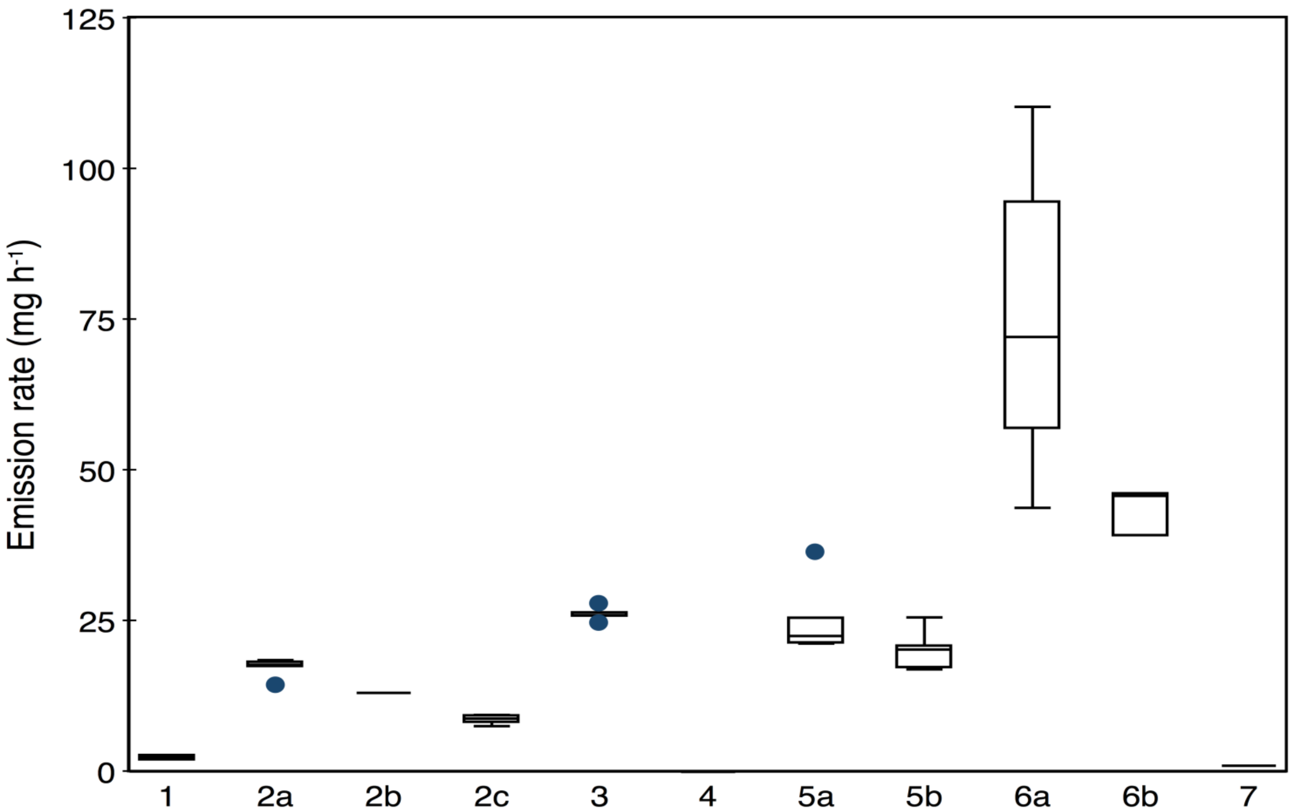
Task 2

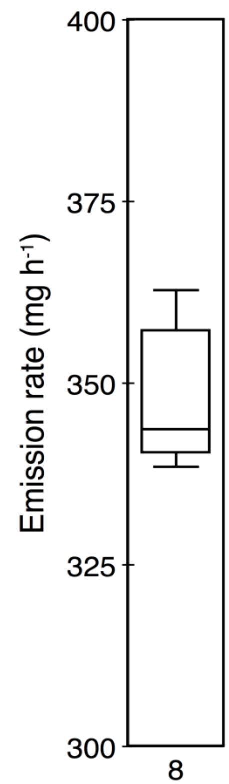
- Qualification of test apparatus
  - MQL = 2.3 mg h^{-1}
  - Repeatability (shown Device 5)



Task 2

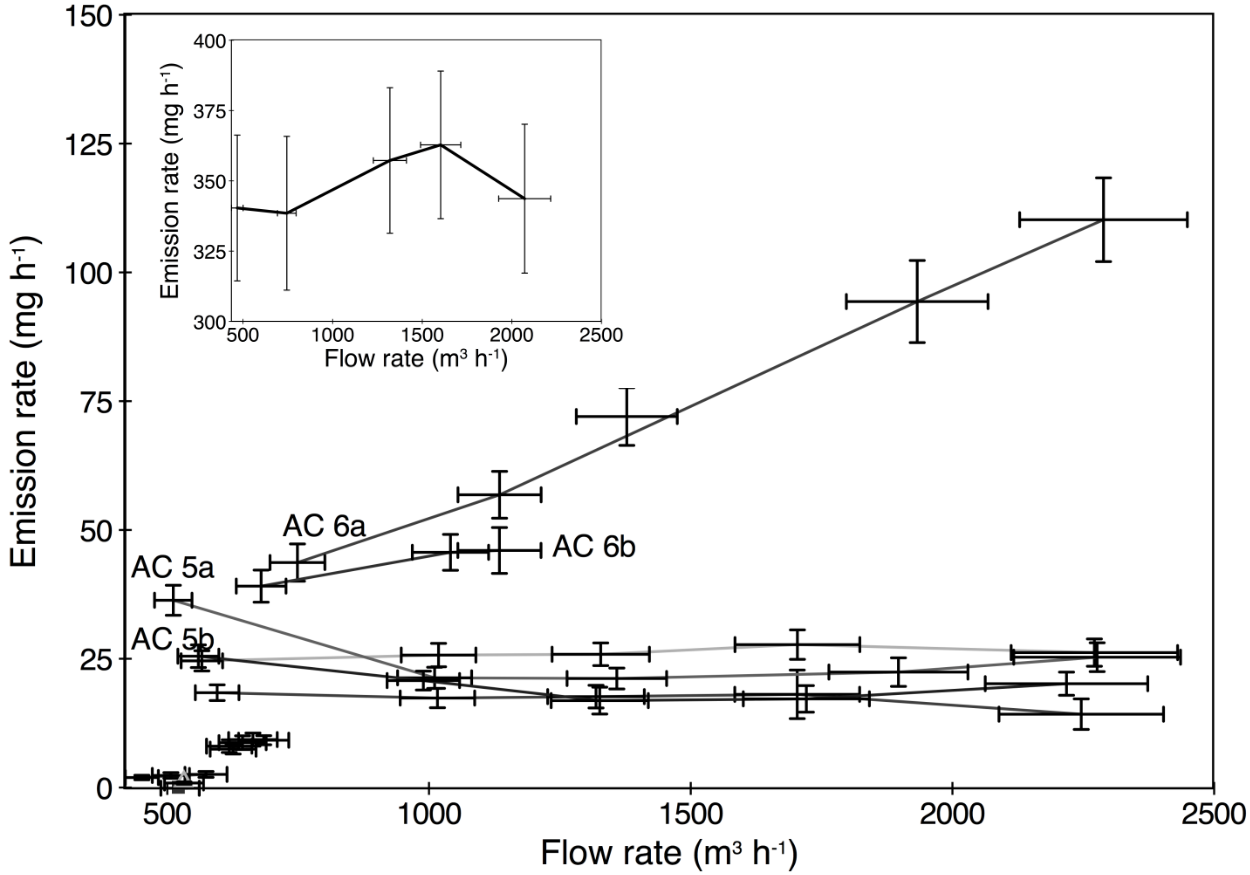
- Emission rate results





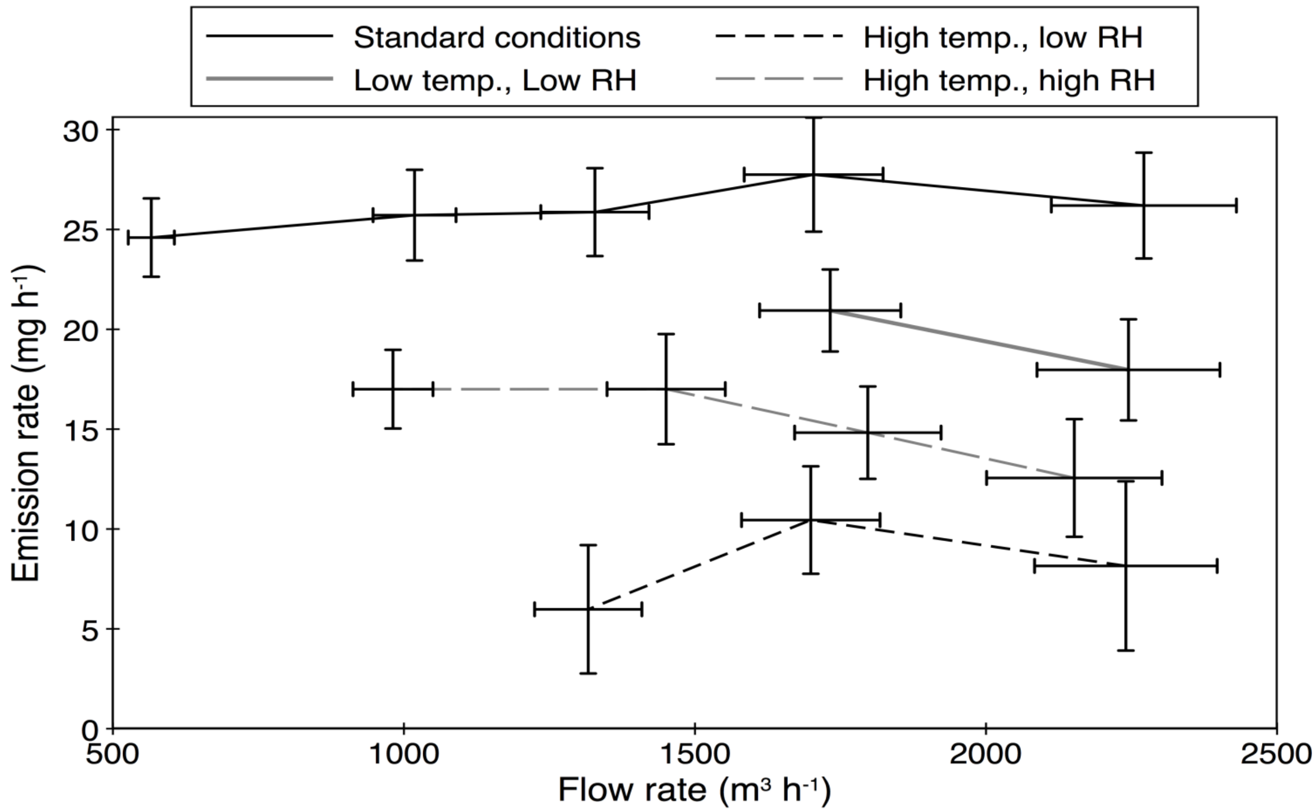
Task 2

- Emission rate dependence on flow rate



Task 2

- Dependence of emission rate on T, RH and flow rate (air cleaner 3)

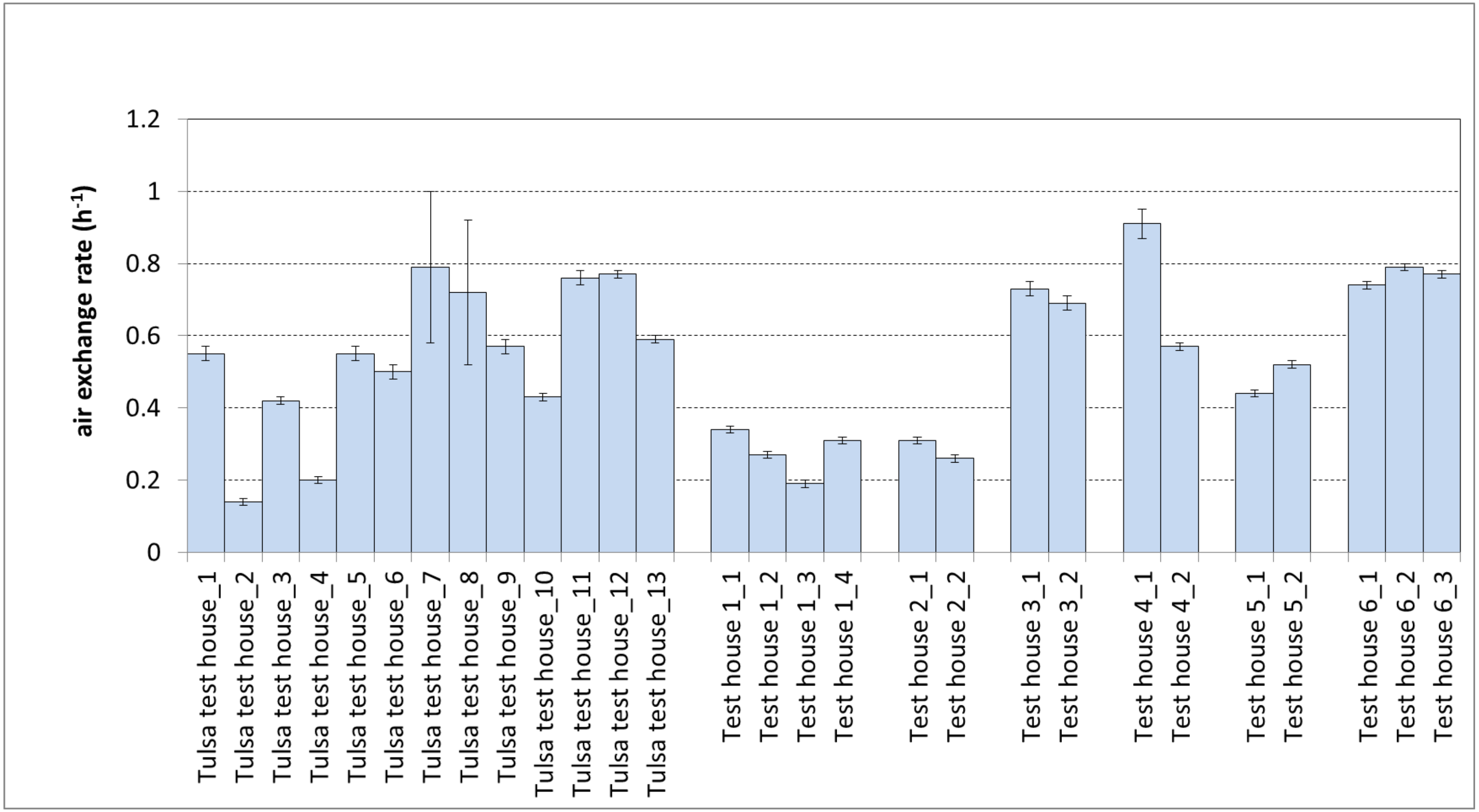


Task 2: Summary of results

- Emission rates vary from < MQL to 350 mg h^{-1}
- Highest emission rates from “ozone generators” using UV lamps
- Two devices exhibited flow dependence (opposite directions)
- One device exhibited temperature and RH dependence

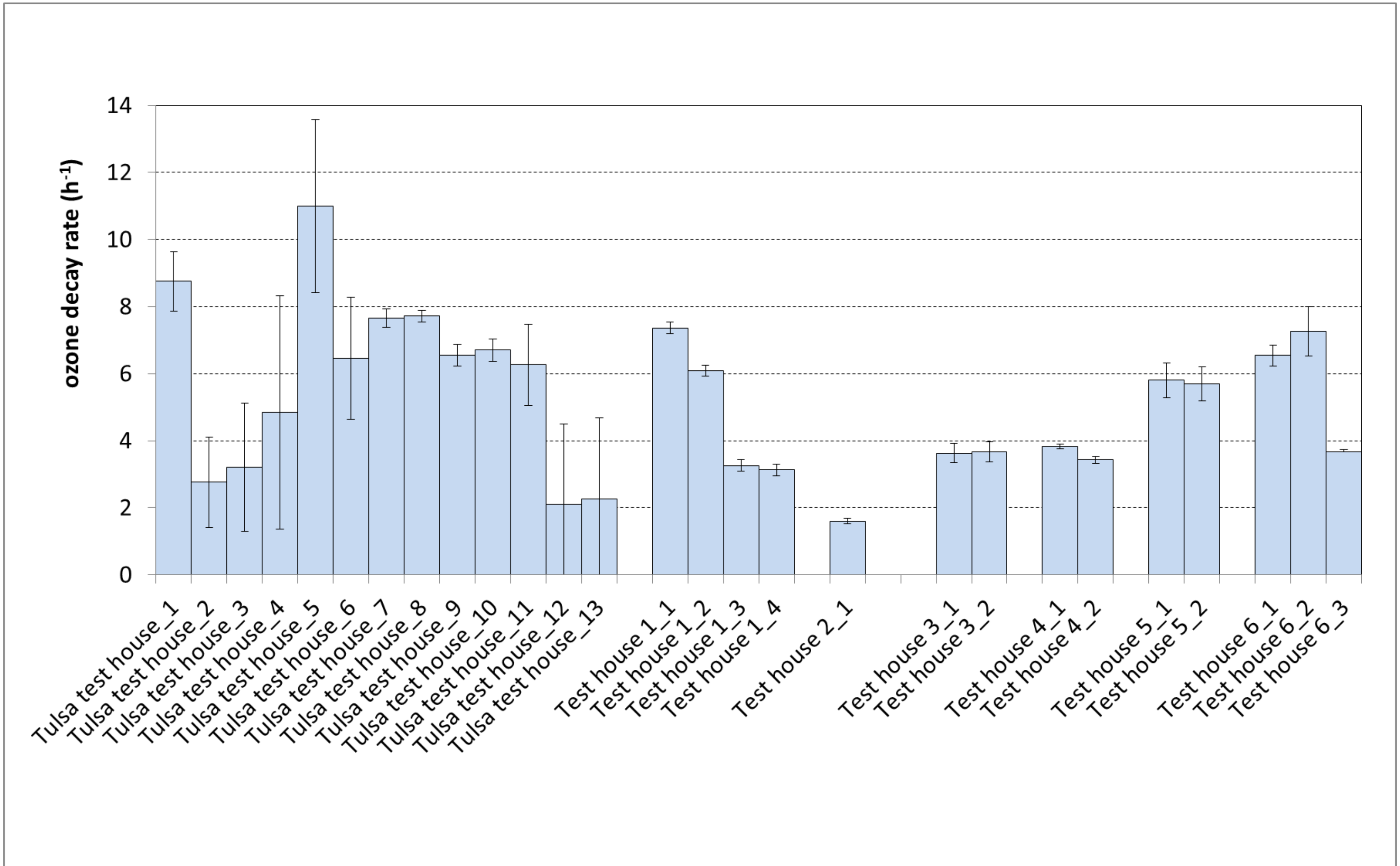
Task 3 and 4

- House characteristics: air exchange rates



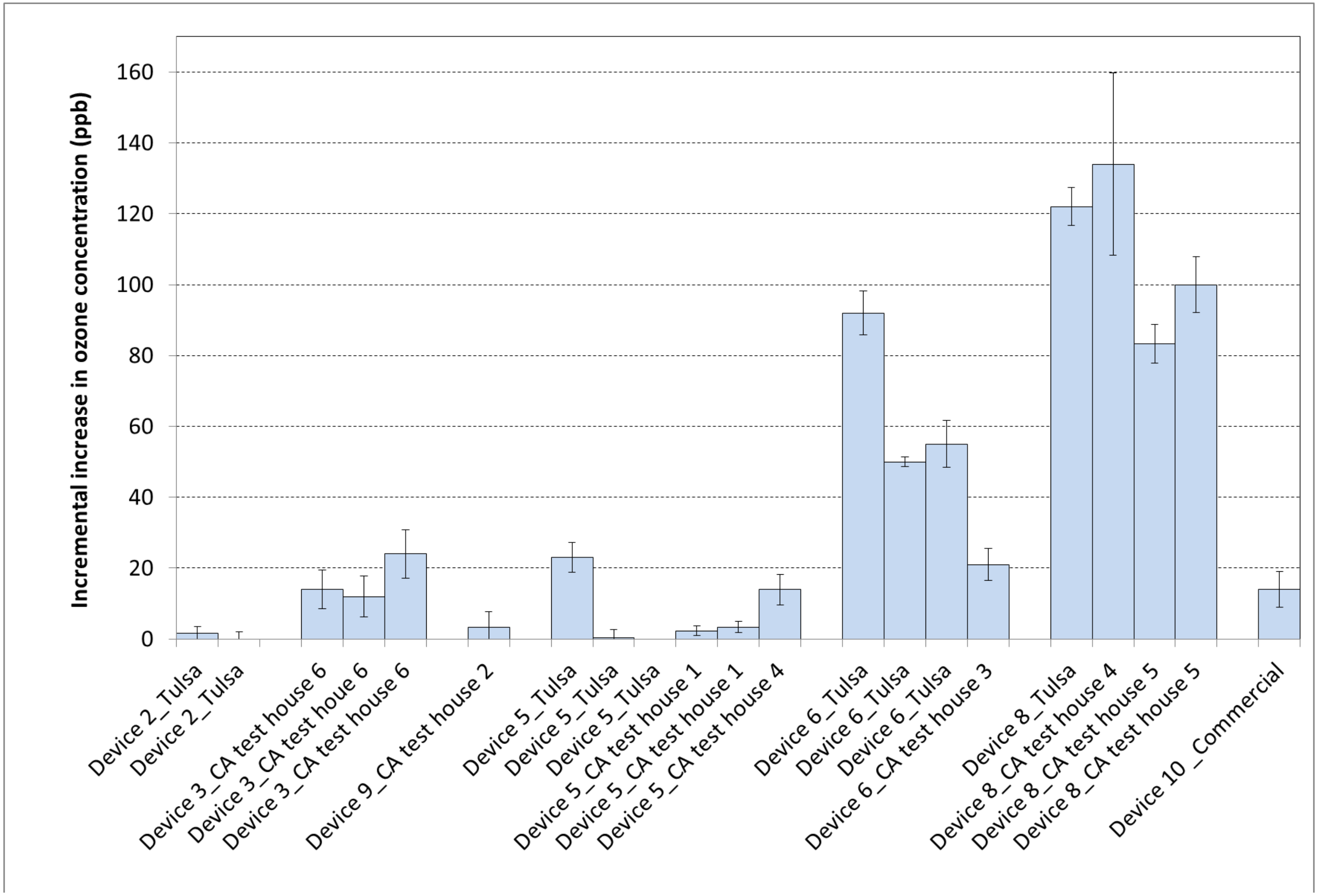
Task 3 and 4

- Field tests: ozone decay rates



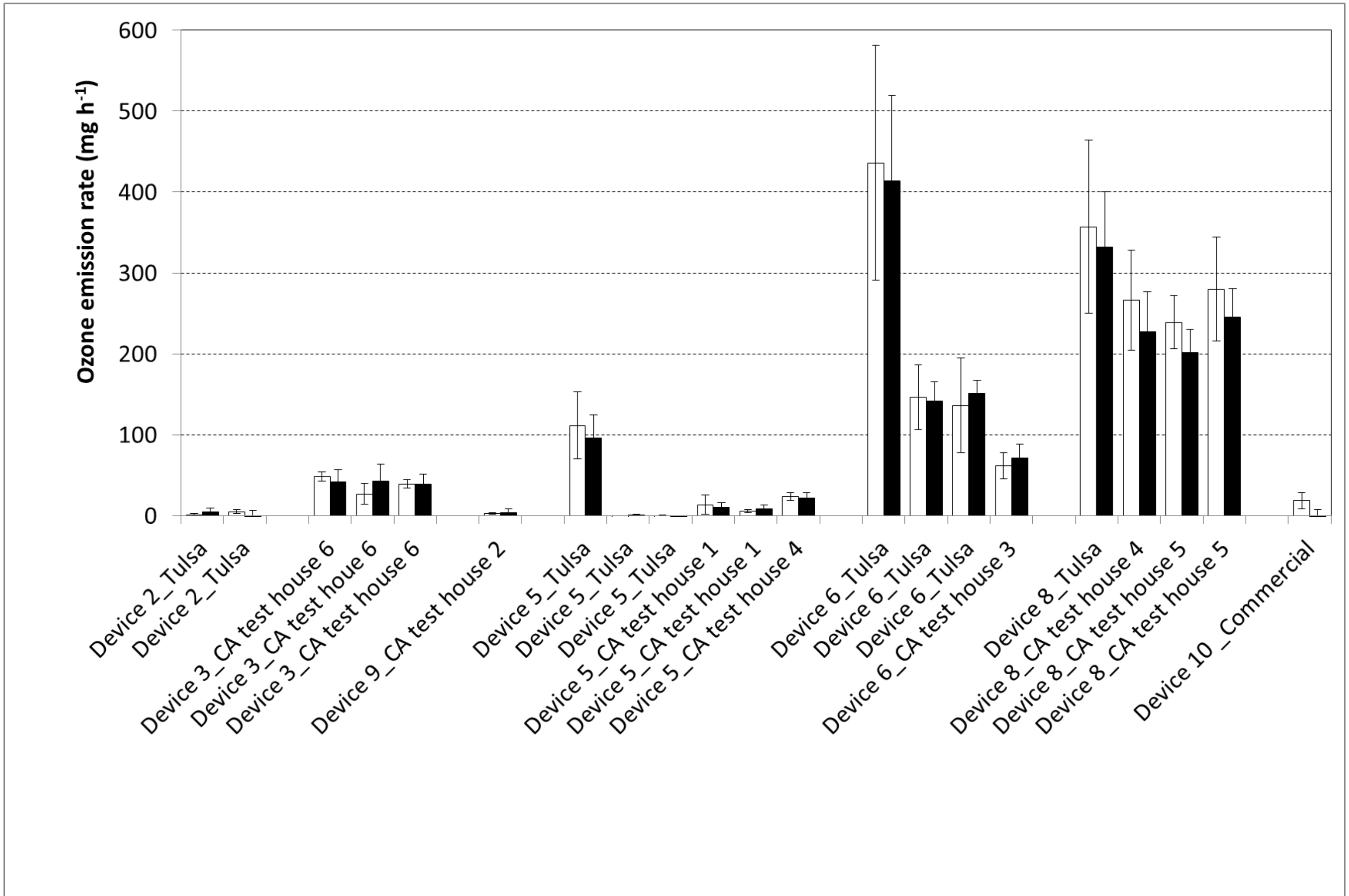
Task 3 and 4

- Field tests: incremental increase in ozone



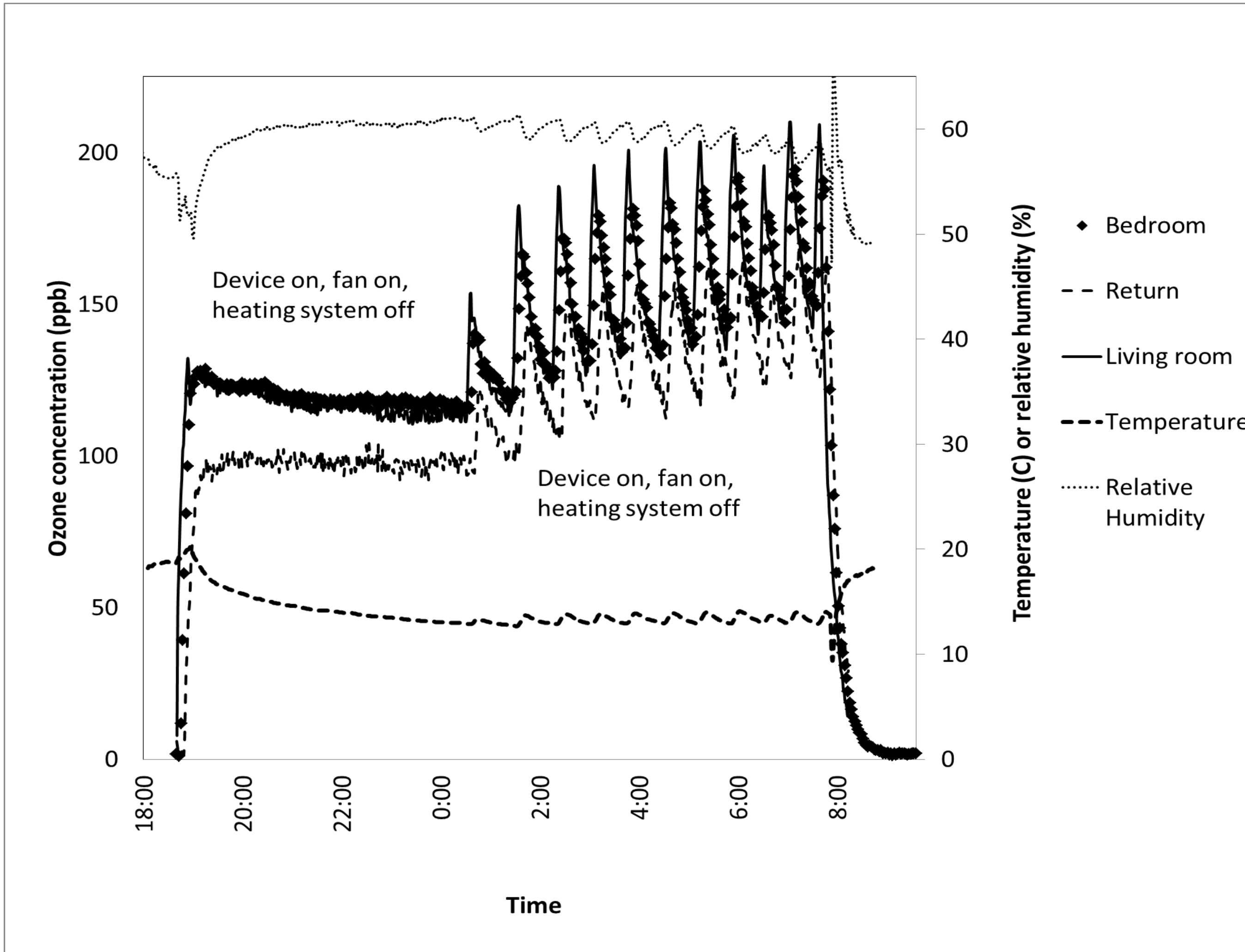
Task 3 and 4

- Ozone emission rates (OER 1 and 2)



Task 3 and 4

- Evidence of temperature dependence (Device 8)

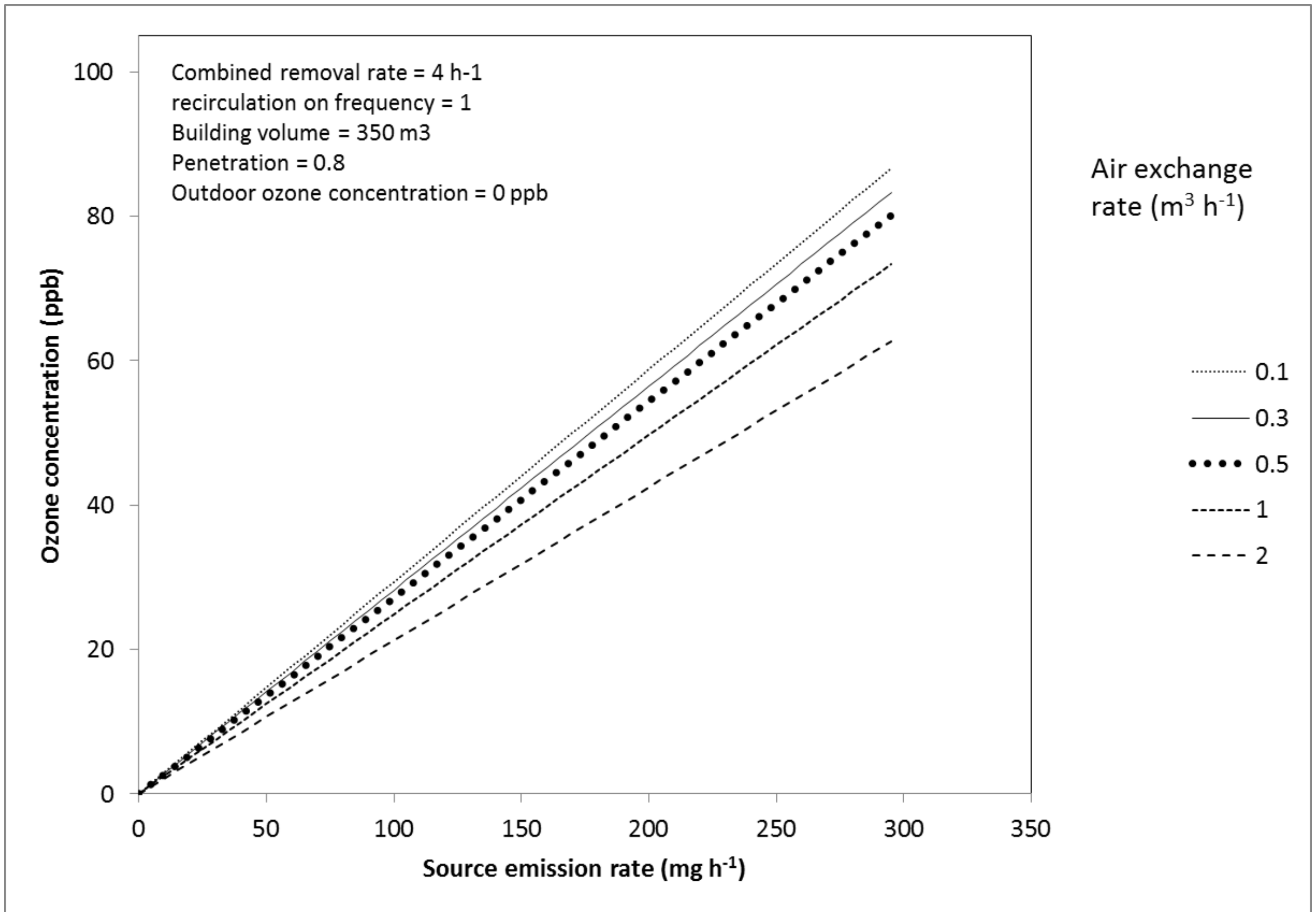


Task 3 and 4: Summary of results

- Field method developed in Tulsa test house
- Two devices increased indoor ozone > 50 ppb
  - Both were intentional ozone generators using UV lamps
- Same two devices exhibited emission rates > 100 mg h^{-1} in multiple homes
- Evidence of temperature effect
  - Peak concentration >200 ppb for device 8

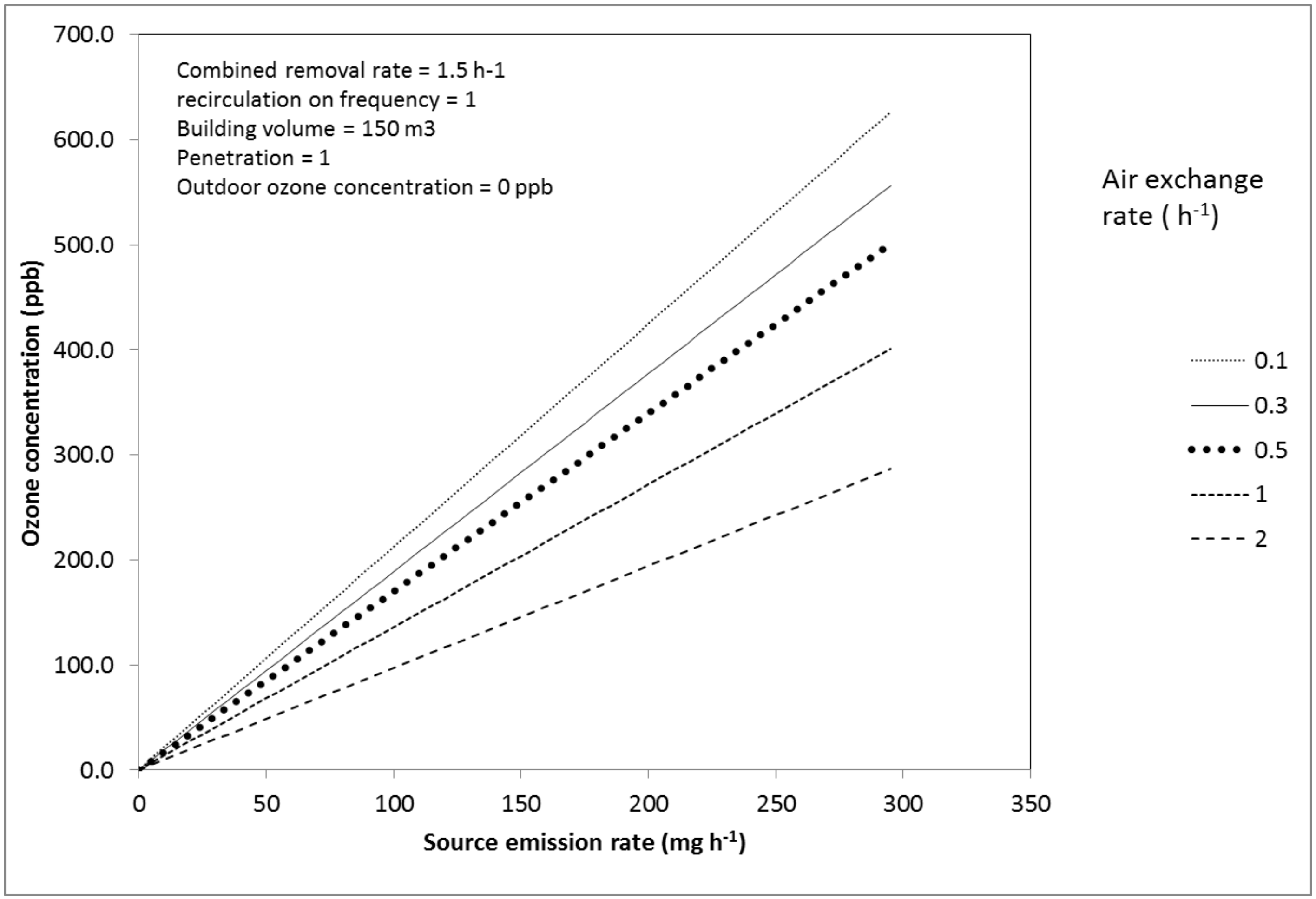
Task 5

- Single zone model: standard house



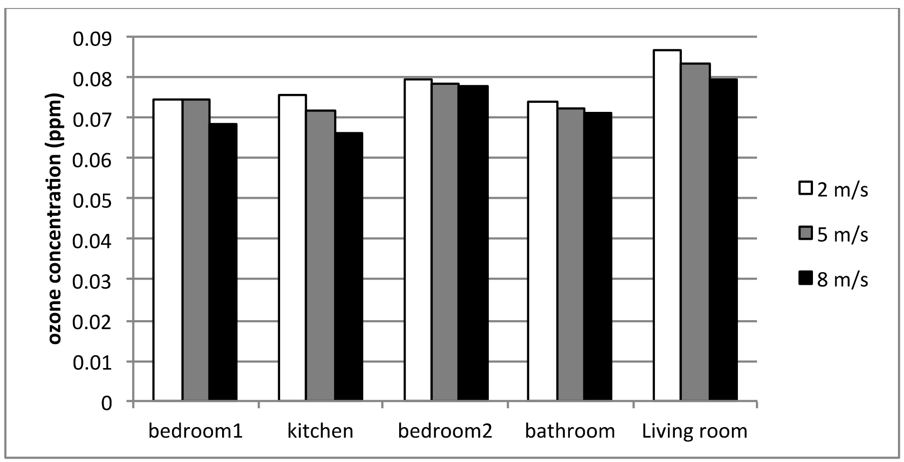
Task 5

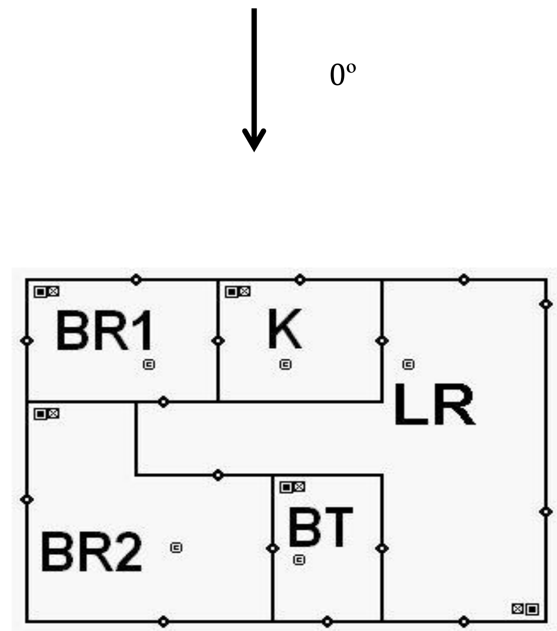
- Single zone model: at risk house



Task 5

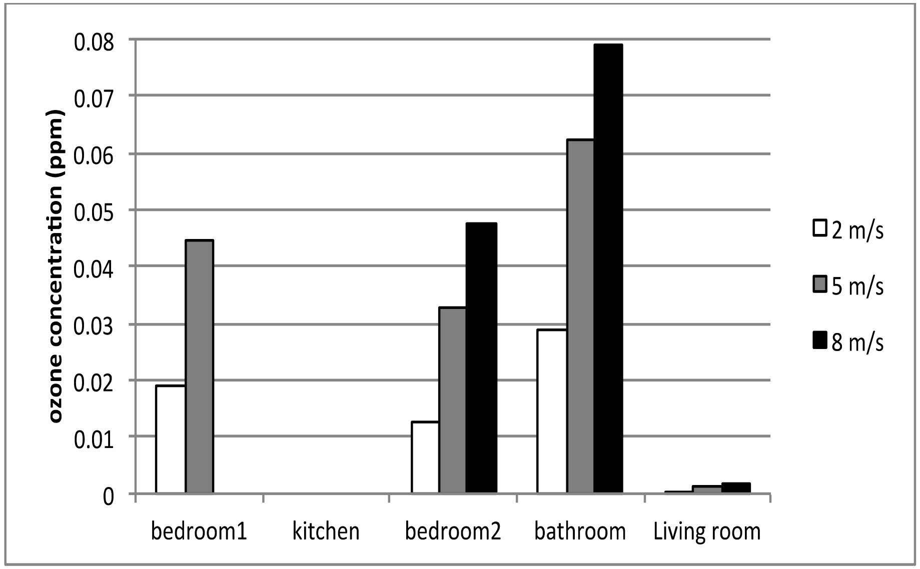
- Multiple zone
  - 100 % AHU on, steady state

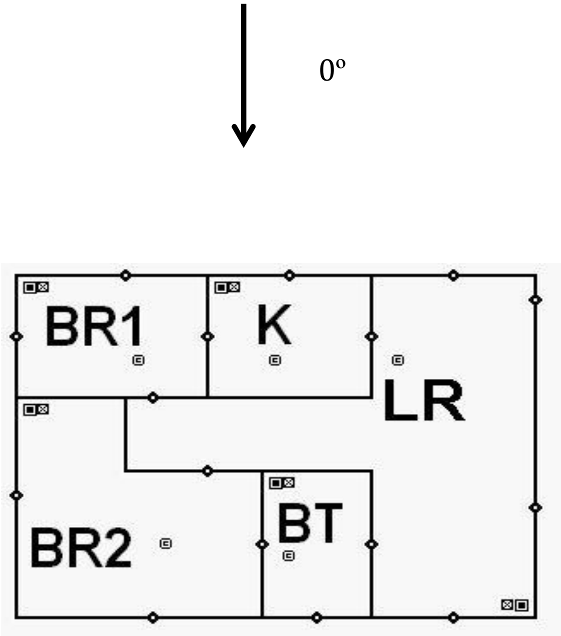




Task 5

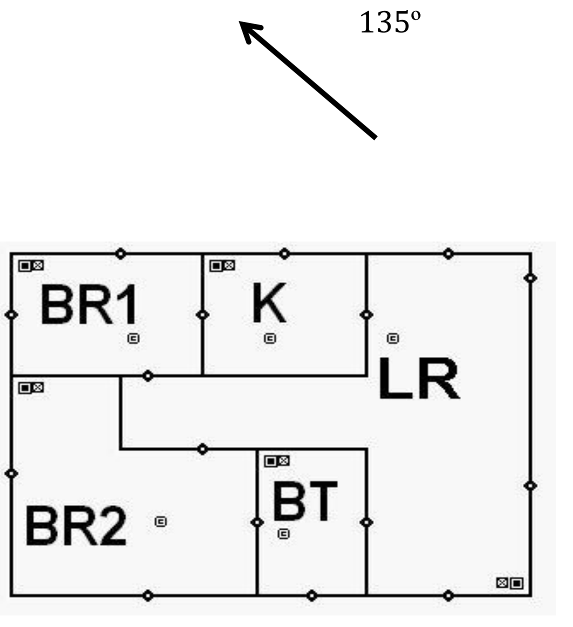
- Multiple zone model
  - AHU off, device on
  - Steady state

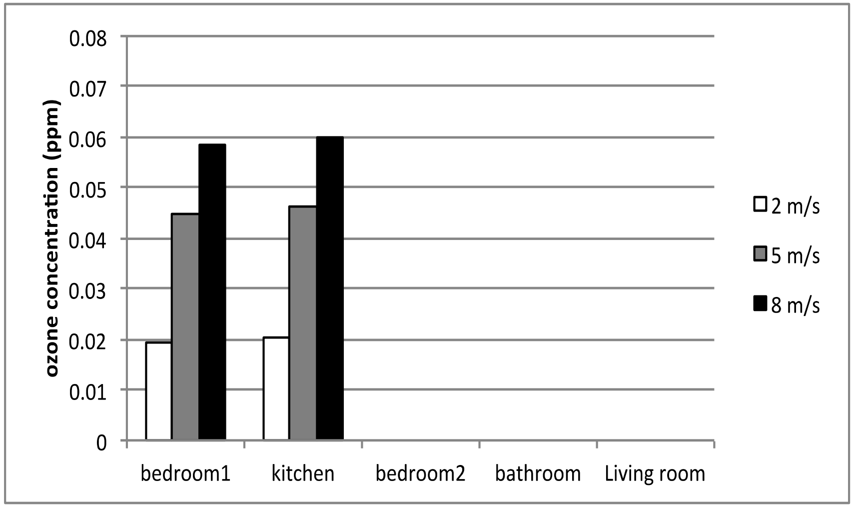




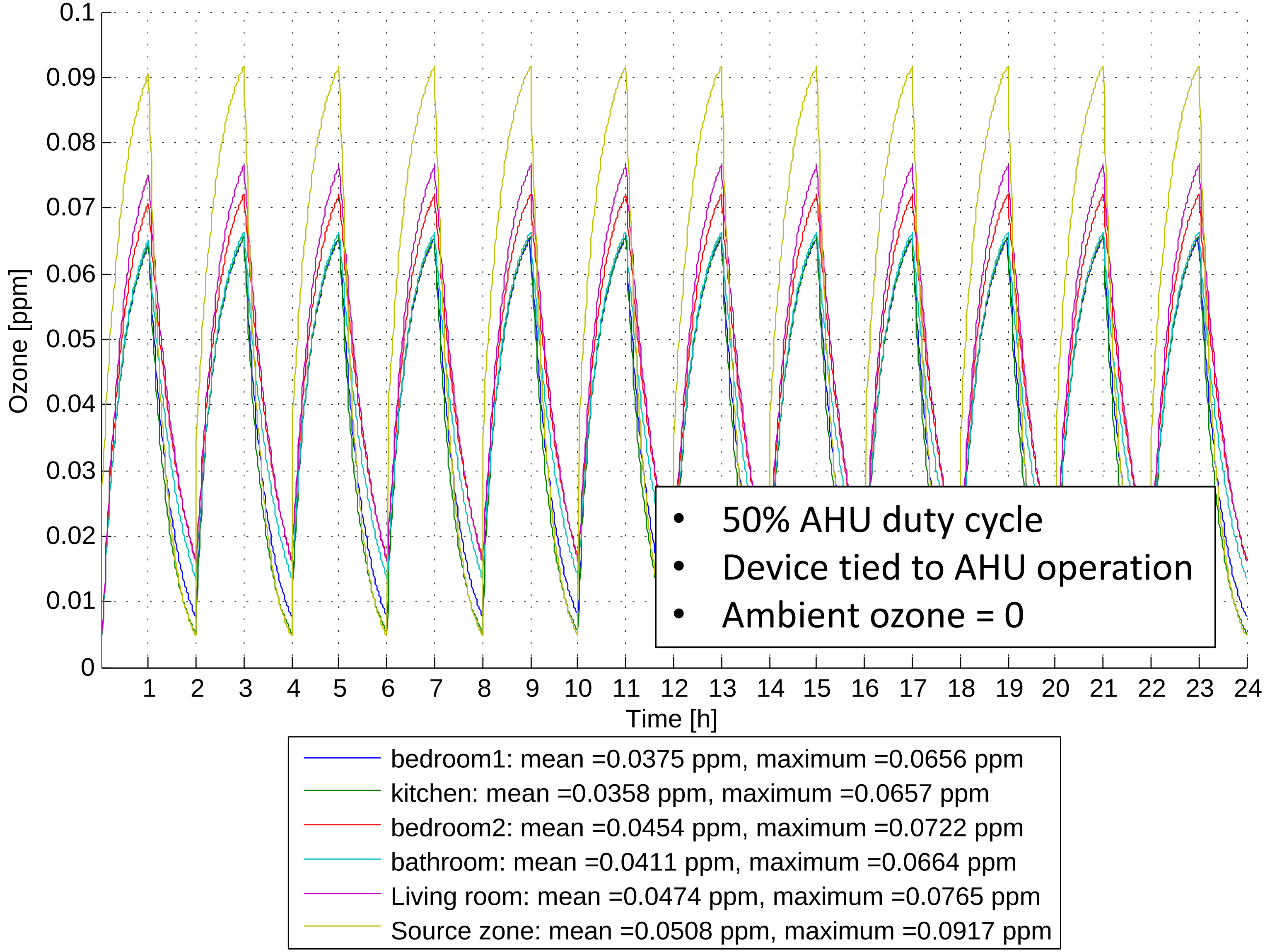
Task 5

- Multiple zone model
  - AHU off, device on
  - Steady state





Task 5: dynamic results

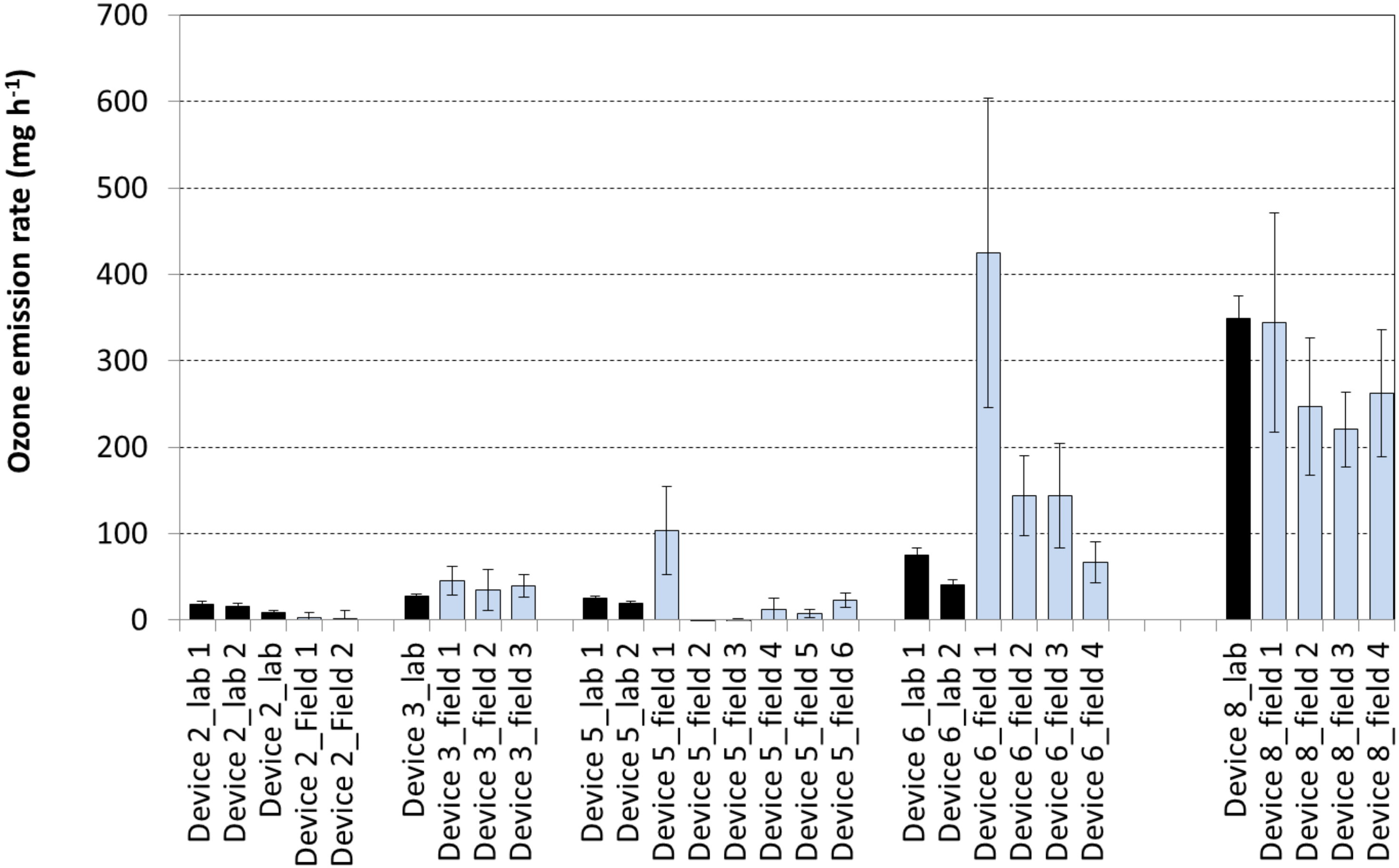


Task 5 summary

- Single zone model
  - Standard home: need ~150 mg/h to achieve 50 ppb
  - At risk home: need ~ 27 mg/h to achieve 50 ppb
- Multiple zone model
  - Wind direction can result in substantial differences among rooms
  - Short-term peaks can occur when AHU turns on

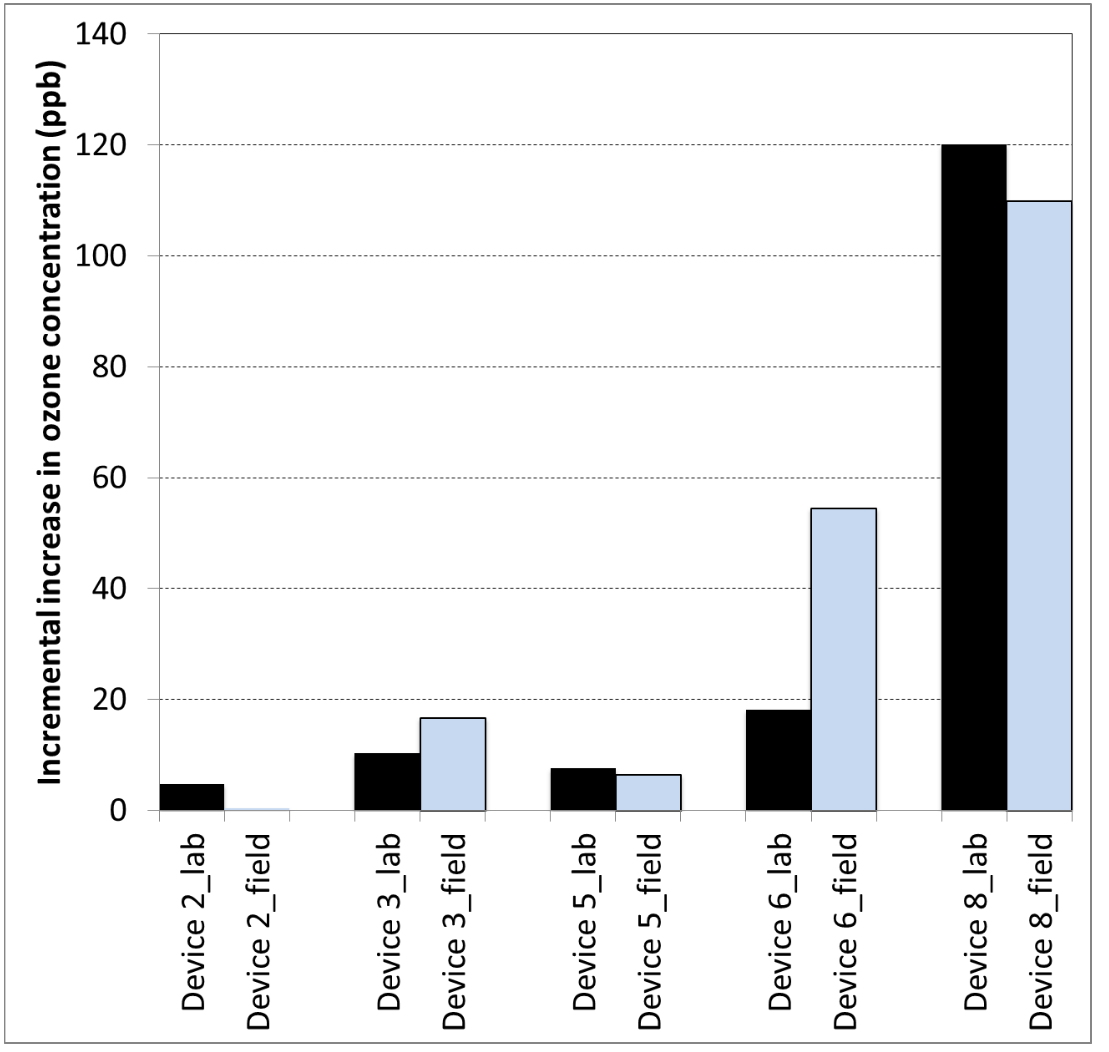
Discussion

- Comparison field/laboratory



Discussion

- Predicted and realized incremental increase in ozone



Summary

- Test method and apparatus
- Device testing
  - 12 devices
  - Emission rates ~ < 2.3 to > 350 mg h^{-1}
- Field tests
  - Incremental concentration increase up to 170 ppb
  - Some devices had erratic emission rates
- Simulations
  - Small, low reactivity, low AER houses more at risk
  - Typical house requires 150 mg h^{-1} to reach 50 ppb

Conclusions

- Electrically connected in-duct devices can increase residential ozone concentrations > 50 ppb
  – Further field tests not necessary
- Laboratory test method adequate to predict field impact
- Need better understanding of installed device occurrence
  – Consumer installation of devices

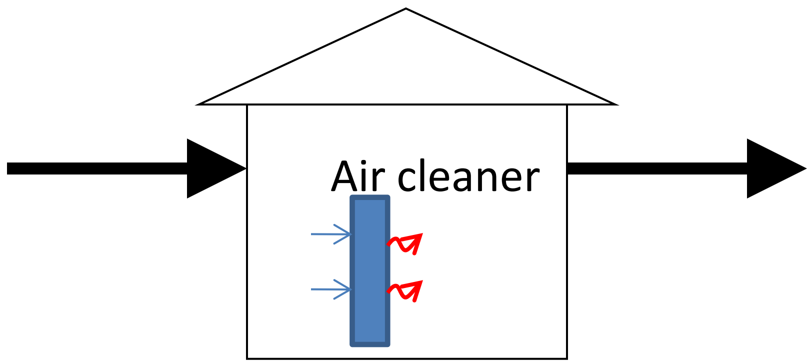
Acknowledgements

- California Air Resources Board
- Occupants and homeowners
- David Reisdorph, Nishanthini Vijayakumar Shakila, Adcharee Karnjanapiboonwong, Mikhil Shetty, Atila Novoselac, Kristia Parker, Joshua Rhodes, Megan Gunther, Christina Phensy, Mark Jackson, Shahana Khurshid, April Rocha
- Deborah Bennett, UC Davis
- Jonathan Reyes, Sawyer Heating
- Donations from dealers and manufacturers

Questions?

Extra slides

Indoor ozone concentration depends on device emission rate, *S*



Outdoor ozone concentration

Penetration

$$C_{indoors} = \frac{\lambda C_{outside} P + S}{V(\lambda + k_d)}$$

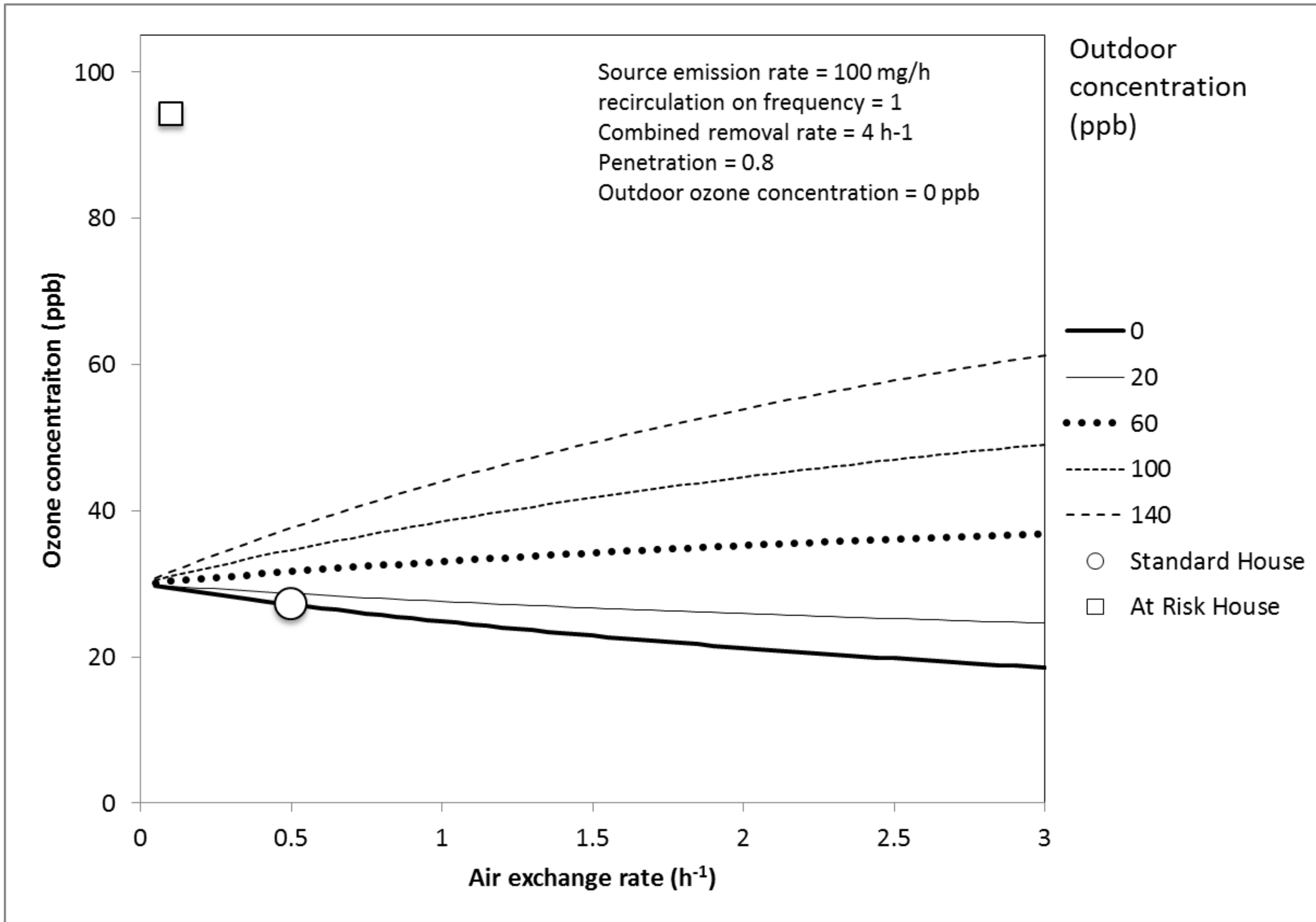
Device emission rate

Air exchange rate

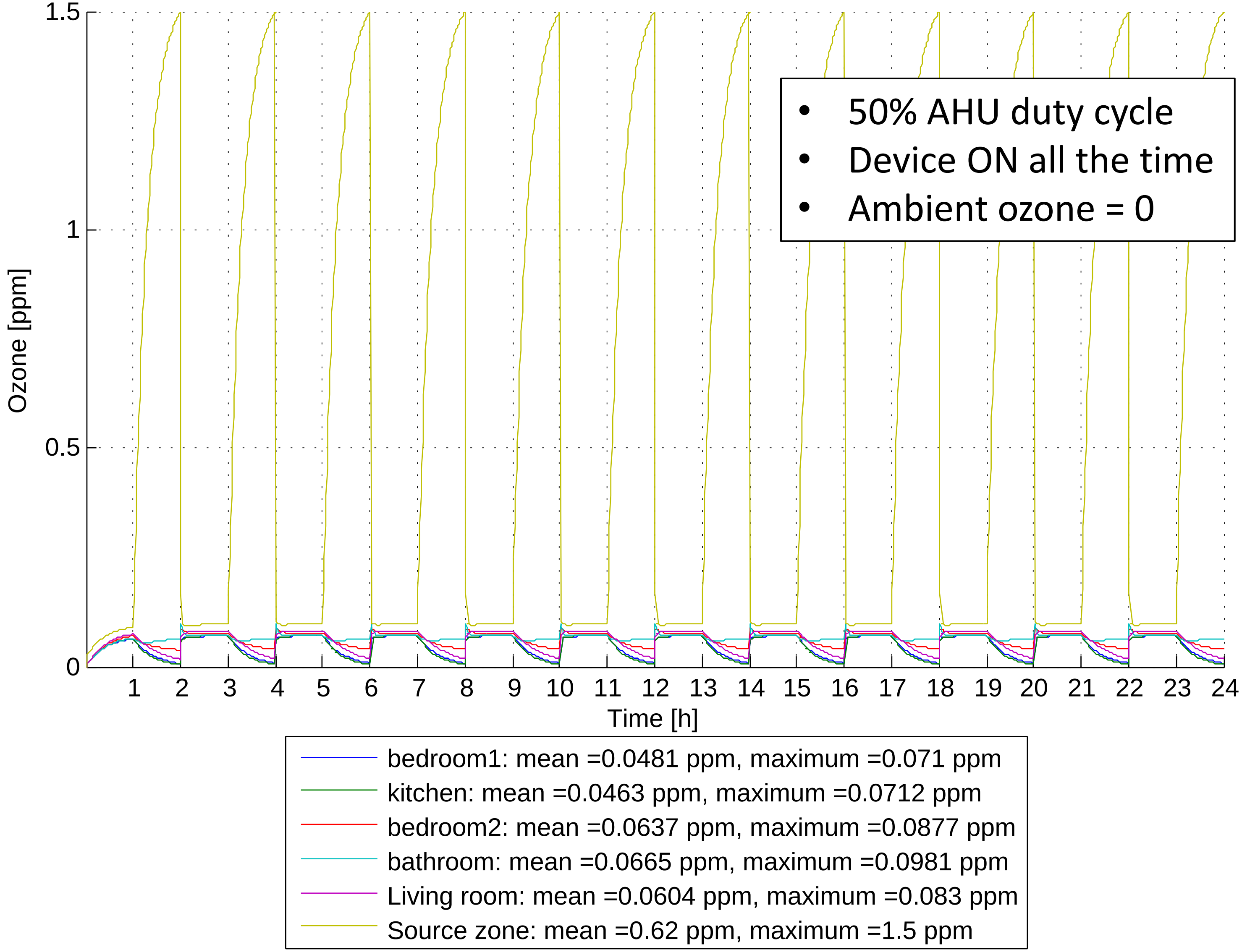
Ozone decay rate (reactions with surfaces)

Task 5

- Single zone model: influence of ambient O_3

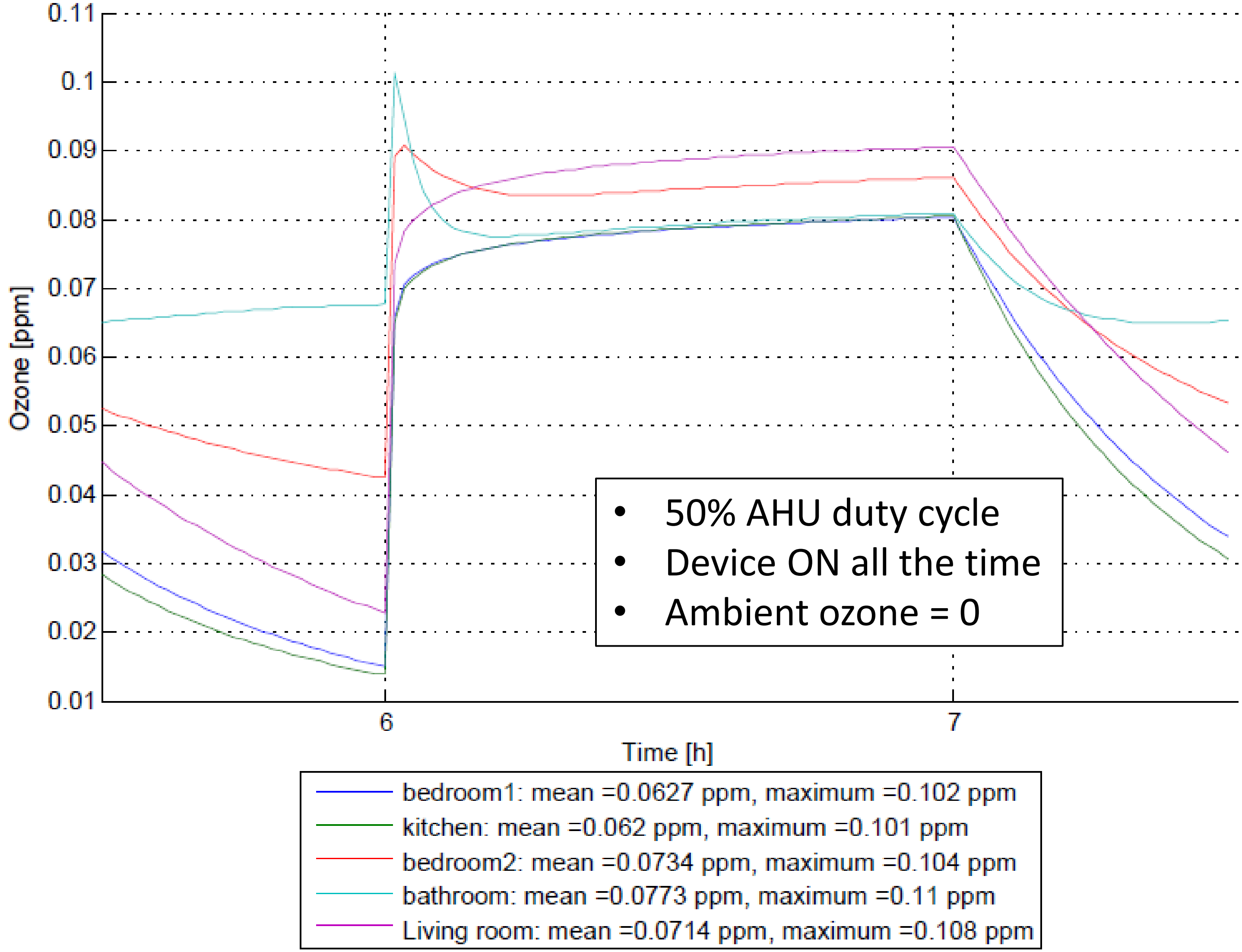


Task 5: dynamic results



- 50% AHU duty cycle
- Device ON all the time
- Ambient ozone = 0

Task 5: dynamic results



Task 5: dynamic results